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Extreme Precipitation in a Future Climate—Assessing Climate Factors at Sub-daily Scales From Regional Climate Model Projections

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ABSTRACT
The anticipated increase in extreme precipitation is expected to be one of the most important impacts of climate change in Danish cities. Hence, guidelines on how these changes can be incorporated in urban design practice are required. This paper compiles all the new information available on climate projections at sub-daily scales and re-evaluates the current guidelines. The information compiled includes three statistical downscaling methods, an ensemble of regional climate models (RCMs) and four different emission scenarios. This study highlights that a relatively large amount of the data available is not suited to the needs of urban drainage design. Therefore, statistical downscaling methods that can accommodate these needs are necessary. The three statistical downscaling methods used here agree on an expected increase of extreme precipitation at both sub-daily and daily scales. However, the changes estimated are subject to large uncertainties, mainly arising from the RCMs and emission scenarios. To account for the uncertainties, both mean and high climate factors are provided in the new guidelines. This study discusses the difficulty of an objective selection of recommended changes and emphasises the need of expert knowledge to combine all the information and account for uncertainties.

KEYWORDS
Climate change, extreme precipitation, sub-daily, RCM, statistical downscaling

INTRODUCTION
Changes in extreme events are expected to be one of the most important impacts of the anticipated future climate change in cities (Fowler and Hennessy, 1995). In Denmark, both the intensity and frequency of extreme precipitation events are expected to increase (Christensen and Christensen, 2002; IPCC, 2012). Guidelines on how these changes can be incorporated in urban design practice were published by the Danish Water Pollution Committee in 2008 (Arnbjerg-Nielsen, 2012). These changes, referred to as climate factors (CF), are commonly expressed as the relative change from present to future conditions of extreme precipitation intensity. The CFs for 2100 recommended in the 2008 guideline are 1.2, 1.3 and 1.4 for 2- , 10- and 100-year design events, respectively.

The understanding of the global climate system and computational capabilities has increased considerably in recent years. More and improved information is now available to estimate CFs. The increase in information has also eased the assessment of the uncertainties associated to CFs. Hence, the currently recommended CFs need to be revaluated and compiled in a new set of guidelines for urban designers, which must also include an estimate of the associated uncertainties.

Uncertainties in CFs arise from several sources. The main ones are: selection of emission scenario, global circulation model (GCM) and/or regional climate model (RCM), and statistical downscaling method (Maraun *et al.*, 2010). GCMs are the primary source of information in climate studies. They simulate the response of the global climate system to a specific climate forcing scenario. A range of forcing scenarios has been defined by the IPCC. The new Representative Concentration Pathways (RCPs) substitute the previous SRES emission scenarios defined in 2000 (Moss *et al*,. 2010).

The spatial resolution of the GCMs (approximately 150 km) is too coarse for addressing climate change impacts at the local scale. For this reason, RCMs are commonly used. These are physical models similar to GCMs but set up to cover a specific region (e.g. Europe) at a higher spatial resolution (approximately 25 km). RCMs use GCMs as boundary condition to simulate the climate system under future conditions. Even though the spatial resolution in the RCMs is higher than in the GCMs, it is still too coarse for simulating extreme precipitation at the urban scale. Additionally, RCMs often inherit biases from the GCMs. For these reasons, further statistical downscaling is needed to obtain high-spatial resolution bias-corrected projections. In recent years, a wide range of statistical downscaling methods has been suggested in the literature (see reviews by Fowler *et al.* (2007) and Maraun *et al.* (2010)). Large multi-model ensembles of RCMs have also been made available, e.g. the European project ENSEMBLES (van der Linden and Mitchell, 2009).

Multi-model ensembles of RCMs provide useful information to estimate the changes and assess the uncertainty in precipitation projections at the local scale. However, most of these data are only available at daily scale. The assessment of changes and associated uncertainties at sub-daily scale is challenging, but crucial because urban floods are mainly caused by extreme precipitation at durations lower than one day.

This paper addresses the challenges in estimating changes in extreme precipitation at sub-daily scales. It focuses on the use of an ensemble of RCMs to derive high-temporal resolution CFs and their associated uncertainties. Extreme precipitation CFs at hourly and daily resolution over Denmark using several approaches are presented here comprising different statistical downscaling methods, RCMs, GCMs and emission scenarios. The main question discussed here is: How can this information be turned into guidelines for urban design practice that communicate both the anticipated change and the inherent uncertainties?

REGIONAL CLIMATE MODELS AND SCENARIOS

A multi-model ensemble of 13 RCMs driven by 6 GCMs with SRES scenario A1B from ENSEMBLES (van der Linden and Mitchell, 2009) at a temporal and spatial resolution of 24 h and 25 km, respectively, is used here (see list of RCMs in Sunyer *et al.*, in preparation). The outputs from the RCMs also include daily 1 h maximum precipitation. While the outputs from these RCMs remain the main data set in the present study, outputs from other RCMs are also used to assess the influence of emission scenario.

Two simulations from the RCM HIRHAM5 driven by EC-EARTH have been made available (Mayer *et al.*, in preparation). One at a spatial resolution of 8 km and temporal resolution of 1 h, and the other at 25 km and 24 h (including daily 1 h maximum precipitation). The results from both simulations are available for two emission scenarios. The model at 8 km is available for RCPs 4.5 and 8.5, and the model at 25 km is available for RCP 4.5 and a 6° global warming scenario (Moss *et al.*, 2010).

Of all the scenarios considered here the 6° global warming is the one with the highest impact. RCP 4.5 is a more optimistic scenario than A1B and is similar to B1. RCP 8.5 is a high-end scenario similar to A2, i.e. slightly below the 6° global warming. The time periods considered for all the RCMs are 1961-1990 and 2071-2100, which are selected to represent present and future conditions, respectively.

STATISTICAL DOWNSCALING METHODS

This section briefly describes the three statistical downscaling methods used here. These were applied in Sunyer *et al.* (in preparation), where they are described in detail. All the methods are used to downscale the RCMs from the ENSEMBLES project and estimate the CF of T-year events for T equal to 2, 10, and 100 years.

Delta change method for extreme precipitation

This method is based on the assumption that the changes in extreme precipitation at the large spatial scale of the RCMs are the same as the ones at the local scale. Hence, it estimates the changes in the T-year events using only RCM outputs. In this case, the outputs used are the daily 1 h maximum precipitation and daily precipitation.

First, the T-year events for present and future are estimated from the RCMs for each land grid point over Denmark. Extreme value series are defined using a Partial Duration Series methodology, where an average of 3 events per years was applied to select the extreme values. A regional estimation procedure is applied by fitting a Generalized Pareto distribution to the extreme value series. Then, the CF is calculated as the relative change of the T-year event estimates from the two series.

Weather Generator combined with disaggregation

The Neyman-Scott Rectangular Pulses (NSRP) weather generator (WG) implemented in the RainSim software (Burton *et al.*, 2008) is used here to generate daily time series for present and future conditions. This WG represents precipitation as clusters of precipitation cells. Precipitation properties (daily mean precipitation, variance, skewness, and probability of dry day) are used to estimate the parameters of the model. The WG is fitted separately for each grid point of the observed precipitation data set Climate Grid Denmark (CGD) (Scharling, 2012). The precipitation properties for the future period are estimated by perturbing the properties estimated from CGD using the changes projected by the RCMs.

The canonical cascade model described in Molnar and Burlando (2005) is then used to disaggregate the daily WG generated data into a temporal resolution of 30 minutes. The parameters of the cascade are estimated using high-temporal resolution station data from the Danish SVK data set (Jørgensen *et al.*, 1998). It must be noted that the cascade model calibrated for present period is used to disaggregate time series for the future period, i.e. changes in the relation between short and long duration precipitation are not considered. Finally, CFs are calculated as the ratio between 1 h T-year event estimates from the generated time series for future and current conditions, respectively, using the same extreme value analysis procedure as applied in the delta change method.

Climate analogue
This method identifies a region where the present conditions are analogous to the future climate conditions in Denmark. It uses a metric based on a set of climate indices: mean and variance of temperature and precipitation, proportion of dry days, and extreme value statistics. The metric is defined as the difference between the indices for the future in Denmark and the present period in Europe. For the present period, the indices are estimated using the gridded data set E-OBS (Hofstra *et al.*, 2009). For the future, each index is estimated using the regional average change over Denmark projected by the RCMs.

T-year events from hourly data from the region selected using the metric are used to represent future extreme precipitation in Denmark. In this study, the region identified is the north west of France. CFs are estimated as the ratio between the T-year events from the identified region and the T-year event estimates for present conditions in Denmark.

RESULTS AND DISCUSSION
This section analyses the CFs at hourly and daily resolution found using the statistical downscaling methods described above in combination with different RCMs and emission scenarios. Additionally, the CF selection and the challenge of defining guidelines that combine all the results are discussed.

Statistical downscaling method
Figure 1 shows the mean CFs and the 68% confidence interval (CI) for 2, 10, and 100 year return periods estimated from the three statistical downscaling methods. The 68% CI is estimated from combining the results of all the RCMs and grid points. For the climate analogue (CA) method, CIs cannot be shown because only one estimate is obtained. In addition, CFs could only be estimated for the 2 and 10-year return periods for hourly precipitation from the available information at the analogue stations.

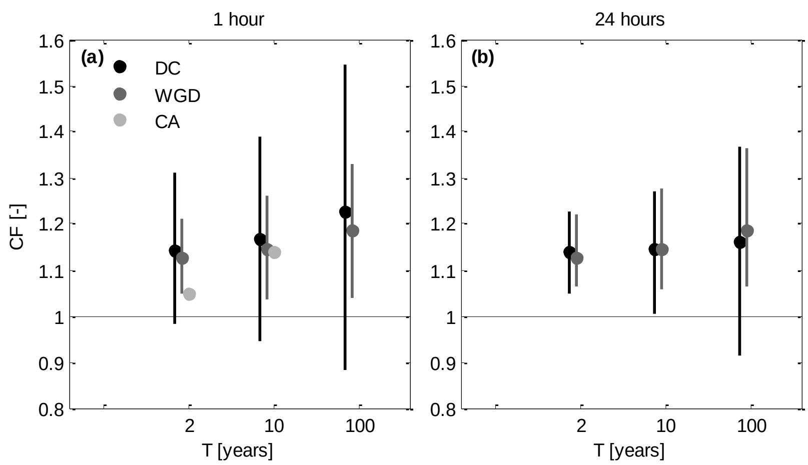

Figure 1. CFs found for each statistical downscaling method (DC in black, WGD in dark grey, and CA in light grey at 1 h (a) and 24 h (b). The circles represent the mean CF and the lines represent the 68% confidence interval.

All the methods point towards an increase in precipitation intensity for all return periods at both hourly and daily resolution. The mean CF found for the delta change method (DC) and the weather generator combined with disaggregation (WGD) is similar for all return periods and temporal resolutions. The results from CA are lower for the 2 year return period but rather similar for the 10 year return period. Larger uncertainty and larger differences between the methods are obtained for higher return periods.

The CI in DC is larger than in WGD, especially in the hourly results. This is due to extreme precipitation outputs from the RCMs (used in DC) are less robust than the mean precipitation properties (used in WGD). In the case of the hourly results, this is also because only daily RCM outputs (which are more robust than hourly outputs) are used to estimate hourly CFs. This illustrates the main advantage and disadvantage of WGD. The advantage is that it estimates changes in extreme precipitation using more robust information from the RCMs than the information used in DC. The disadvantage is that only changes at daily scale are used to generate hourly time series for the future, and changes at daily and hourly resolution will most likely not be the same (as shown in the DC approach).

Climate models

Figure 2 shows the regional average of the CFs found for DC and WGD for each RCM. The results from the GCM ECHAM5 and the RCM HIRHAM5 are highlighted in the figure. This allows us to briefly discuss whether the differences in CFs arise from the GCMs or RCMs.

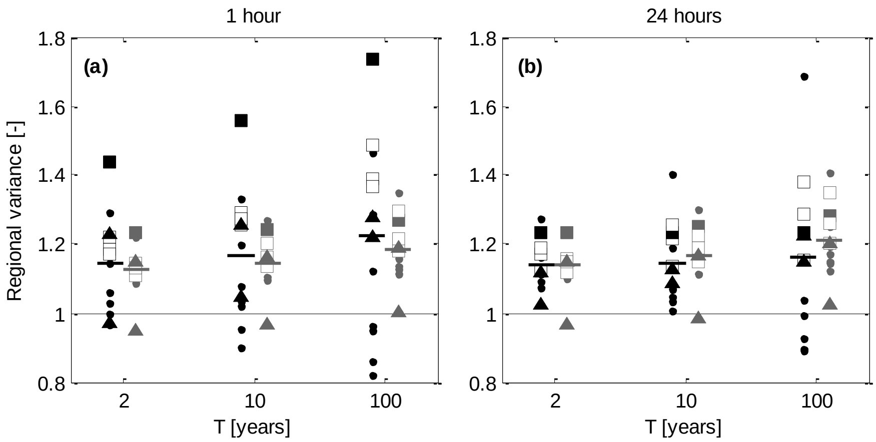

Figure 2. Regional average of each statistical downscaling method (black for DC and grey for WGD) and RCM at 1 h (a) and 24 h (b). The mean of all the RCMs is shown with a line. The squares show the RCMs driven by ECHAM5 and the triangles the HIRHAM5 RCMs. HIRHAM5-ECHAM5 is shown with a filled square.

The four RCMs driven by ECHAM5 lead to changes approximately equal or larger than the average for both methods and temporal resolutions. On the other hand, large differences are found between the three HRHAM5 RCMs, showing both positive and negative changes. At hourly resolution, HIRHAM5-ECHAM5 leads to CFs much larger than the other RCMs in DC but not in WGD. This seems to indicate that the GCMs and statistical downscaling method have a larger influence on the magnitude of the CF than the RCMs. It also illustrates the importance of considering an ensemble of RCMs driven by different GCMs and use of different statistical downscaling methods.

The analysis of the results in Figure 1 and 2 assumes that the RCMs are independent and that their bias remains constant from present to future. These two issues have often been discussed in the literature (e.g. Knutti *et al.,* 2010). Sunyer *et al.* (2013; in revision) showed that these RCMs from ENSEMBLES are interdependent and that the bias is not constant. Both the assumption of constant bias and interdependency have an influence on the value and uncertainty of the CFs. Figure 3 shows the results from Sunyer *et al.* (in revision) for a return period of approximately 0.15 years. The uncertainty found when the RCMs are assumed interdependent and the bias not constant is significantly larger than when assuming independence and constant bias.

Climate scenario

This section compares the CFs obtained using the ENSEMBLES RCMs (which use A1B) and HIRHAM-ECEARTH run using RCP 4.5, 8.5 and the 6° scenarios. Figure 3 compares all the CF values available. The DC method has been applied to calculate CFs for the 25 km resolution simulations, whereas the results from the 8km resolution simulations are taken from Sørup *et al.* (in review).

At hourly resolution, the 6° scenario leads to the largest CFs (increases of up to 270%) followed by RCP8.5 (up to 230%). The difference between the scenarios is larger than the variability found for the A1B ensemble, and much larger than the difference between the statistical downscaling methods. Similar results are obtained for the daily CFs, but in this case the difference between the scenarios is much smaller. The CFs found using the 6° scenario are smaller than for the RCP 8.5. In the case of HIRHAM-ECEARTH using RCP 4.5, the results from the model at 8 km are much larger than at 25 km.

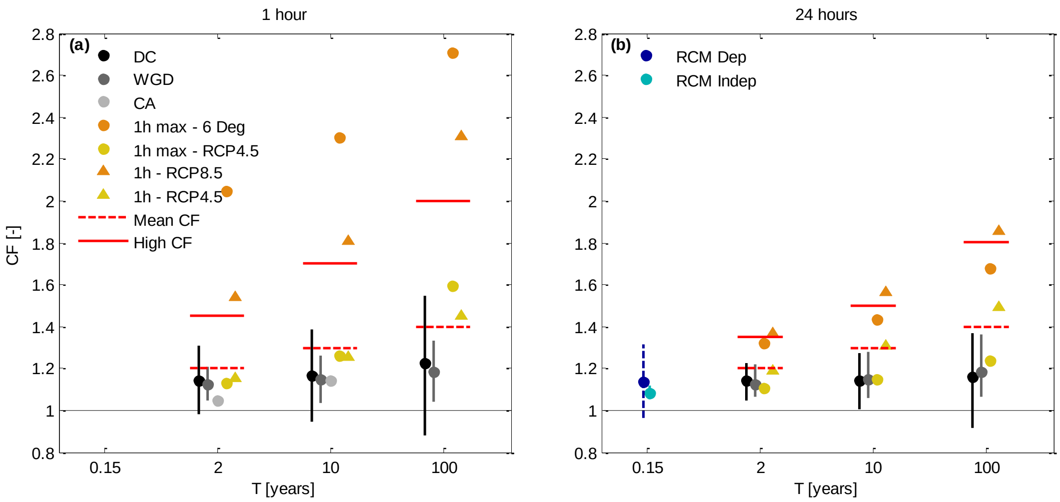

Figure 3. Summary of all CFs found for different statistical downscaling method, RCMs and emission scenarios at 1 h (a) and 24 h (b). The mean CF is shown using circles for the methods using RCMs at 25 km, while triangles are used for RCMs 8 km spatial resolution. The lines represent the 68% confidence interval. RCM Dep and Indep are the results from Sunyer *et al.* (in revision) and refer to the assumption RCM interdependency and changing bias, and independency and constant bias, respectively. Mean CF and high CF are the recommended CFs in this study.

Climate factor selection

The previous sections have assessed the information available from different sources for estimation of CFs and the corresponding uncertainty. This section summarizes the reasoning followed to select the CFs suggested as guideline for urban drainage design. In order to reflect the uncertainty in the CFs, it was decided to select two values: a mean CF that represents the expected future, and a high CF that reflects the uncertainty and the possibility of a more extreme future situation.

The analysis of the different climate models has shown the importance of using a multi-model ensemble of RCMs driven by several GCMs. Here a relatively large ensemble of different RCMs, statistical downscaling methods, and emission scenarios has been considered. However, not all the possible combinations are available, e.g. the RCMs have not been run for all GCMs and emission scenarios. Therefore, it must be stressed that the selection of CFs cannot be fully objective.

In most cases, for both temporal resolutions the currently recommended CFs (1.2, 1.3 and 1.4 for the 2- , 10- and 100-year, respectively) lie within the CIs of the A1B ensemble using the different statistical downscaling methods. However, the currently recommended CFs are higher than the mean CF based on the A1B ensemble. The different methods and models used partially influence this difference. The HIRHAM model that was used in the currently recommended CFs leads to larger values than the ensemble average. However, it is likely that the main difference is because A1B is used here and A2 was used for the currently recommended CFs. The influence of the emission scenario in the CFs shown in Figure 3 supports this hypothesis. A relevant fact to take into account is that since 2000, the emissions have been slightly higher than anticipated in A2 (Peters *et al.*, 2013). Hence, it was deemed reasonable to select as a mean CF a value higher than the actual mean CF based on the A1B ensemble. With all this in mind, it was decided that there is not enough evidence to change the currently recommended CFs, also considering that keeping the same values facilitates the urban planners' tasks. Hence, the mean CF in the new guidelines has been chosen to be the same as the currently recommended CF values.

The high CF recommended is based on the confidence limits found for the A1B ensemble and two main considerations: (i) all CF calculations in this study assume independent RCMs and constant bias and hence might underestimate the uncertainty related to the ensemble spread and introduce a negative bias; (ii) the large CFs obtained from the high-end scenarios. For these two reasons, the high CF is chosen to be larger than the upper confidence limit found for the A1B ensemble. Additionally, the results indicate that CFs depend on the temporal resolution (higher CFs for hourly resolution), which was judged to be of significance for the high CFs. The high CFs recommended in the new guidelines are: 1.45, 1.7, and 2 for hourly and 1.35, 1.5 and 1.8 for the daily resolution (see Figure 3).

CONCLUSIONS

The aim of this study was to use the recently developed information to update the guidelines for urban drainage design considering climate change. For this purpose, several RCMs, statistical downscaling methods, and emission scenarios were analysed. The main conclusions from the study are:

- A relatively large amount of data and methods are available, but they are not suited to the needs of urban drainage design. Therefore, statistical downscaling methods that allow the estimation of hourly CFs from daily outputs are needed.
- The three downscaling methods considered here lead to similar results even though they use different RCM outputs and assumptions. This adds confidence in the results.
- The choice of RCM and emission scenario has a high impact on the calculated CFs. Hence, several RCMs and emissions scenarios must be taken into account.
- A simple way of incorporating the large uncertainties in the guidelines is to provide a mean and a high CF. However, an objective selection of these CFs is currently impossible. Expert knowledge is needed to combine all the information available and account for the uncertainties.

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REFERENCES

Arnbjerg-Nielsen K. (2012). Quantification of climate change effects on extreme precipitation used for high resolution hydrologic design. *Urban Water J.*, 9, 57–65.

Burton A., Kilsby C.G., Fowler H.J., Cowpertwait, P.S.P., O'Connell, P.E. (2008). RainSim: A spatial–temporal stochastic rainfall modelling system. *Environ. Model Softw.*, 23, 1356–1369.

Christensen J.H., Christensen O.B. (2002). Severe summertime flooding in Europe. *Nature*, 421, 805–806.

Fowler A., Hennessy K. (1995). Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Nat. Hazards*, 11, 283–303.

Fowler H.J., Blenkinsop S., Tebaldi C. (2007). Linking climate change modelling to impacts studies : recent advances in downscaling techniques for hydrological. *Int. J. Climatol.*, 1578, 1547–1578.

Hofstra N., Haylock M., New M., Jones P.D. (2009). Testing E-OBS European high-resolution gridded data set of daily precipitation and surface temperature. *J. Geophys. Res.*, 114, D21101.

IPCC (2012). Summary for Policymakers. In: Field CB, Barros V, Stocker TF, et al. (eds) Manag. Risks Extrem. Events Disasters to Adv. Clim. Chang. Adapt., Special Re. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp 1–19.

Jørgensen H.K., Rosenørn S., Madsen H., Mikkelsen P.S. (1998). Quality control of rain data used for urban runoff systems. *Water Sci. Technol.*, 37, 113–120.

Knutti R., Furrer R., Tebaldi C., Cermak J., Meehl, G.A. (2010). Challenges in Combining Projections from Multiple Climate Models. *J. Clim.*, 23, 2739–2758.

Maraun D., Wetterhall F., Ireson A.M., Chandler R.E., Kendon E.J., Widmann M., Brienen S., Rust H.W., Sauter T., Venema V.K.C., Chun K.P., Goodess C.M., Jones R.G., Onof C., Vrac M., Thiele-Eich, I. (2010). Precipitation downscaling under climate change. Recent developments to bridge the gap between dynamical models and the end user. *Rev. Geophys.*, 48, RG3003.

Mayer S., Maule C.F., Sobolowski S., Christensen O.B., Sørup H.J.D., Sunyer M.A., Arnbjerg-Nielsen K., Barstad I. (in preparation). Added value from high-resolution mini-ensemble climate simulations over Scandinavia

Molnar P., Burlando P. (2005). Preservation of rainfall properties in stochastic disaggregation by a simple random cascade model. *Atmos. Res.*, 77, 137–151.

Moss R., Edmonds J., Hibbard K., Manning M., Rose S., van Vuuren D., Carter T., Emori S., Kainuma M., Kram T., Meehl G., Mitchell J., Nakicenovic N., Riahi K., Smith S., Stouffer R., Thomson A., Weyant J., Wilbanks T. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, 463, 747–756.

Peters G.P., Andrew R.B., Boden T., Canadell J.G., Ciais P., Le Quéré C., Marland G., Raupach M.R., Wilson C. (2013). The challenge to keep global warming below 2 °C. *Nature Climate Change*, 3, 4–6.

Sunyer M.A., Madsen H., Rosbjerg D., Arnbjerg-Nielsen K. (2013) Regional Interdependency of Precipitation Indices across Denmark in Two Ensembles of High-Resolution RCMs. *J. Clim.*, 26, 7912–7928.

Sunyer M.A., Gregersen I.B., Madsen H., Rosbjerg D., Arnbjerg-Nielsen K. (in preparation). Comparison of different statistical downscaling methods based on Regional Climate Models for estimating changes in hourly extreme precipitation

Sunyer M.A., Madsen H., Rosbjerg D., Arnbjerg-Nielsen K. (in revision). A Bayesian approach for uncertainty quantification of extreme precipitation projections including climate model interdependency and non-stationary bias. *J. Clim*.

Sørup, H.J.D., Christensen, O.B., Arnbjerg-Nielsen, K. and Mikkelsen P.S. (in review) Modelling high resolution precipitation fields using a spatial neyman-scott weather generator. *Atmos. Res.*

van der Linden P. and Mitchell J. F. (2009). Ensembles: Climate change and its impacts: Summary of research and results from the ensembles project, Technical report, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.